

RESEARCH LETTER

10.1002/2014GL062654

Key Points:

- Mediterranean-Atlantic exchange flow lowers European coastal sea level
- Sea level can be used to measure Mediterranean-Atlantic exchanges
- Processes in the Strait of Gibraltar strongly influence European mean sea level

Supporting Information:

- Figures S1 and S2

Correspondence to:

C. W. Hughes,
cwh@liv.ac.uk

Citation:

Hughes, C. W., R. J. Bingham, V. Roussenov, J. Williams, and P. L. Woodworth (2015), The effect of Mediterranean exchange flow on European time mean sea level, *Geophys. Res. Lett.*, 42, 466–474, doi:10.1002/2014GL062654.

Received 2 DEC 2014

Accepted 8 JAN 2015

Accepted article online 11 JAN 2015

Published online 27 JAN 2015

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

The effect of Mediterranean exchange flow on European time mean sea level

Chris W. Hughes^{1,2}, Rory J. Bingham³, Vassil Roussenov¹, Joanne Williams², and Philip L. Woodworth²
¹School of Environmental Sciences, University of Liverpool, Liverpool, UK, ²National Oceanography Centre, Liverpool, UK,

³School of Geographical Sciences, University of Bristol, Bristol, UK

Abstract Using a suite of ocean model simulations and a set of dedicated twin experiments, we show that the exchange flow between the Mediterranean and the North Atlantic leads to a drop in time mean European coastal sea level along the Atlantic coast north of Gibraltar. The drop is about 7 cm along the Portuguese coast and remains apparent (though reduced) as far north as the Norwegian coast. We also show that Mediterranean time and spatial mean sea level is about 9 cm lower than it would be without the exchange flow (but assuming a small supply from the Atlantic to balance evaporation). Each of these relationships makes possible an estimate of the magnitude of the exchange flow based on sea level measurements, and estimates of 0.8 and 0.91 sverdrups are made consistent with previous determinations based mainly on current measurements in the Strait of Gibraltar.

1. Introduction

The slope in mean sea level along the coast is subject to stronger constraints than that in open ocean regions. The zero-order balance in the open ocean is geostrophic balance, in which sea level variations (after correction for the inverse barometer effect) are associated with a flow perpendicular to the sea level gradient. There can, however, be no mean flow perpendicular to the coast, so the zero-order balance would imply that there is no sea level slope along the coast. Any such coastal sea level slope must therefore result from ageostrophic processes. As a result, simple analytical models [e.g., *Johnson and Marshall*, 2002; *Huang*, 1988] tend to assume that sea level is constant along eastern boundaries, while being formulated in a way which avoids the more complex question of dynamics near western boundaries. Alternatively, *Godfrey* [1988] and *Godfrey and Dunn* [2010] assume a balance between the wind-driven Ekman transport into the coast and a balancing geostrophic flow away, which suggests that the wind stress controls the eastern boundary slope of depth-integrated dynamic topography, though not directly sea level. However, this assumes an ocean with vertical sidewalls, thus ignoring the possibility of eastern boundary currents, which are known to represent an important component of the temporal variability of coastal sea level [*Bingham and Hughes*, 2012; *Calafat et al.*, 2012].

In reality, the eastern boundary sea level is certainly not level, although it shows a smaller range than that which is observed in deep water near to western boundaries, which can exceed 1 m between tropical and subpolar latitudes. In fact, both observations and models show a drop of about 35–45 cm between a high near the equator and lows at higher latitudes, in both the Pacific and Atlantic oceans [*Woodworth et al.*, 2012]. As we consider the impact of future climate change on coastal flooding, we need to understand the origin of this slope, and the ability of models to maintain it. This is necessary if we are to have confidence that models used in climate projections can give useful information about the boundary response to ocean warming and circulation changes. Furthermore, if we consider the eastern boundary to form the boundary condition with respect to which the open ocean transport can be found by a Sverdrup balance integral, as has been found to work well for low to middle latitudes [*Wunsch*, 2011; *Gray and Riser*, 2014; *Thomas et al.*, 2014], the eastern boundary sea level slope may also have important implications for the ocean's general circulation and its transport of heat and tracers.

A particular exception to the geostrophic constraint, in the case of the eastern Atlantic, is the exchange with the Mediterranean through the Strait of Gibraltar at approximately 36°N. Water can flow through this gap in the eastern boundary, permitting the formation of a step in eastern boundary sea level between the southern side in Morocco and the northern side in Spain. The Strait is less than 15 km across at its narrowest,

Table 1. Ocean Models Used and Their Main Characteristics

Label	Heritage	Run	Resolution (deg)	Grid	Reference
GECCO	MITgcm		1 × 1	C, no Arctic	Köhl and Stammer [2008]
Occq	OCCAM	202	1/4 × 1/4	B, rotated Atlantic	Marsh et al. [2008]
Occ12	OCCAM	401	1/12 × 1/12	B, rotated Atlantic	Marsh et al. [2009]
Nemoq	OPA	N206	1/4 × 1/4	C, tripolar ORCA	Blaker et al. [2014]
Nemo12	OPA	N001	1/12 × 1/12	C, tripolar ORCA	Blaker et al. [2014]
Livc	MITgcm		1 × 1	C, no Arctic	Williams et al. [2014]
Livst	MITgcm		1/5 × 1/6 ^a	C ^b , no Arctic	Woodworth et al. [2012]
Livnd	MITgcm		1/5 × 1/6 ^a	C ^b , no Arctic	This study
Livwd	MITgcm		1/5 × 1/6 ^a	C, no Arctic	This study

^aIn the North Atlantic, elsewhere spreads gradually to 1 × 1.

^bOnly one grid point in the Strait, other models have two grid points.

or less than a seventh of a degree of latitude, with a sill depth of about 280 m, making it poorly resolved in even the best of global ocean models.

The circulation in the Strait is a complicated exchange flow, with hydraulic control being modulated by strong barotropic and internal tidal currents [Armi and Farmer, 1985; Farmer and Armi, 1989]. The mean flow is into the Mediterranean near the surface and out at depth. Estimates of the exchange transport range from 0.72 to 1.2 Sv (1 Sv = 1 sverdrup = 10⁶ m³ s^{−1}), with strong evaporation over the Mediterranean leading to the outflow being some 4–7% smaller than the inflow [Criado-Aldeanueva et al., 2012]. In one set of measurements, Tsimplis and Bryden [2000] found that the mean exchange interface depth lies at 147 m, although the mean flow reverses direction at a shallower depth of about 127 m. This difference reflects the importance of tidal correlations between flow and interface depth, which in their calculation account for over 40% of the exchange flow, a value consistent with observations of transport by internal waves some distance into the Mediterranean [Kinder, 1984], though it is unlikely that such a large wave transport also occurs on the Atlantic side of the Strait as internal tides there are much more linear [Morozov et al., 2002].

We can estimate the sea level signal associated with this inflow if we assume that the depth-integrated transport is given by the surface flow multiplied by a depth H , which would typically be somewhat smaller than the exchange interface depth because the flow must decrease as it approaches that depth. Taking, for example, $H = 100$ m, geostrophic balance then leads to a total transport $T = (\eta_S - \eta_N)(gH/f)$, where η_S and η_N are sea level (inverse barometer corrected) to the south and north of the Strait, respectively, g is acceleration due to gravity, and f is the Coriolis parameter at 36°N. Substituting values for g , H , and f , this leads to $(\eta_S - \eta_N)/T = 8.75$ cm Sv^{−1}. In other words, a 1 Sv inflow would lead to eastern boundary sea level being 8.75 cm lower on the Spanish and Portuguese coast than on the Moroccan coast. This represents a substantial fraction of the total eastern boundary sea level fall between the equator and high latitudes. This step in sea level would be smaller for a larger effective depth H , or if a substantial part of the exchange resulted from tidal correlations rather than appearing in the Eulerian mean.

The purpose of this paper is to look at how coastal sea level is influenced by the Mediterranean exchange flow, by investigating the representation of this step in sea level in a variety of global ocean models. We find a strong relationship between the step and the exchange transport across a group of nine ocean models, an associated drop in Mediterranean mean sea level compared to the North Atlantic, and an influence on coastal sea level which extends thousands of kilometers northward along the coast. We show that these relationships are consistent with sea level observations if the exchange flow is within a few tenths of a sverdrup of 0.85 Sv, consistent with previous determinations.

2. Model Intercomparison

We have assembled results from nine ocean models, with resolution ranging from 1° to (1/12)°. All have a representation of the Strait of Gibraltar, together with an exchange flow, but the Strait is at most two grid points wide (and in two cases is only one grid point, precluding any geostrophic balance in the Strait itself). The models encompass both B-grid and C-grid horizontal discretizations and include free-running simulations, runs with relaxation of the density field (the “Liv” models), and one run (GECCO) which assimilates multiple ocean observations. The salient properties of the different models are summarized in Table 1.

Transports and sea levels were averaged over a common 5 year period, 1996–2000 inclusive, except in the case of three comparison runs (labeled Livst, Livnd, and Livwd in the table), which represent 1 year averages.

Sea level fields from the models were first regridded onto a common, quarter-degree grid, using a simple nearest grid point scheme. The coast was identified using quarter-degree averages of the General Bathymetric Chart of the Oceans bathymetry [IHO IOC and BODC, 2003], and any ocean points not initially filled by the regridding scheme were filled by an iterative method which fills missing points with the average of surrounding valid ocean points. All points neighboring the continental eastern boundary of the Atlantic were identified (excluding the Mediterranean Sea, and following the western coast of the British mainland at the latitudes of the North Sea, as this was found to produce cleaner curves), and profiles of eastern boundary sea level were extracted. A vertical offset was applied to make the mean eastern boundary value over the latitude range 30–35°N equal to zero. The resulting sea level profiles are plotted in Figure 1a.

The 30–35°N reference range was chosen to show clearly the wide range of steps at the latitude of the Strait of Gibraltar, and it is clear that the variation in size of this step is responsible for a large part of the overall variation between models. Using a reference region south of 20°N (Figure S1 in the supporting information), the models show good agreement on the profile over practically all the African coast south of about 24°N, demonstrating a degree of robustness in representing the process controlling boundary slopes in this region. However, they diverge dramatically farther to the north.

For these nine models, we have also determined the strength of the Mediterranean inflow, integrated down to the depth at which the mean flow reverses (the models do not have tides, and we find little sensitivity to using a time-dependent reversal depth). There is a strong correlation of 0.97 ($p = 1.2 \times 10^{-5}$) between this transport and the difference between southern and northern sea level, averaged along the eastern boundary over latitude bands 30°N to 35°N and 37.5°N to 42.5°N, respectively (the two grey bands in Figure 1a). The relationship is shown in Figure 1b, together with the best-fitting linear relationship. This includes a positive offset, consistent with the general poleward fall in sea level which may be seen in most regions away from the Strait, and a gradient of 7.9 cm Sv^{-1} , which would correspond to an effective current depth $H = 112 \text{ m}$ in the simple calculation given above. It is clear that the size of the step at the Strait is strongly determined by the strength of the Mediterranean exchange transport.

The impression given by the curves in Figure 1a is that the step at Gibraltar influences sea level everywhere to the north of the Strait. However, there are many other factors distinguishing the models, and it is impossible to isolate the Mediterranean exchange flow from other influences as the distance from the Strait increases. In order to address this point, we have performed a set of model runs which are identical except for the geometry of the Strait.

3. Twin Experiments

Two of the model runs in Table 1 (Livc and Livst), which have very different exchange flows, were performed as part of investigations into the dynamics of North Atlantic heat content and sea level changes [Williams *et al.*, 2014; Woodworth *et al.*, 2012] and represent a method of calculating fields in dynamic equilibrium with the density field produced by a Met Office analysis of historical temperature and salinity measurements [Smith and Murphy, 2007]. For this purpose, the best compromise between allowing time for dynamical adjustment and preventing the model from drifting too far from the input data was found to involve initialising with the annual mean temperature and salinity analysis, running for 13 months while maintaining a relaxation to the initial fields with a 3 year time constant, and calculating the average over months 2–13.

Livc model run was run at coarse resolution (1°) but had an artificially widened Strait of Gibraltar to allow there to be two grid points across the Strait. Livst represented a similar run, but at $(1/5 \times 1/6)^\circ$ (longitude \times latitude) resolution in the North Atlantic, and with no special consideration given to the Strait, with the result that it was represented by a single grid point with depth of only 135 m, and permitted only a small exchange flow, as seen in Figure 1b. In order to address purely the question of the geometry of the Strait, two runs twinned with Livst were performed: Livnd (narrow, deep) in which the depth in the Strait was increased to 260 m and Livwd (wide, deep) in which the deeper Strait was extended to two grid points wide. These runs were otherwise identical to Livst. It is clear from Figure 1b that including two grid points was the key to producing a realistic exchange flow.

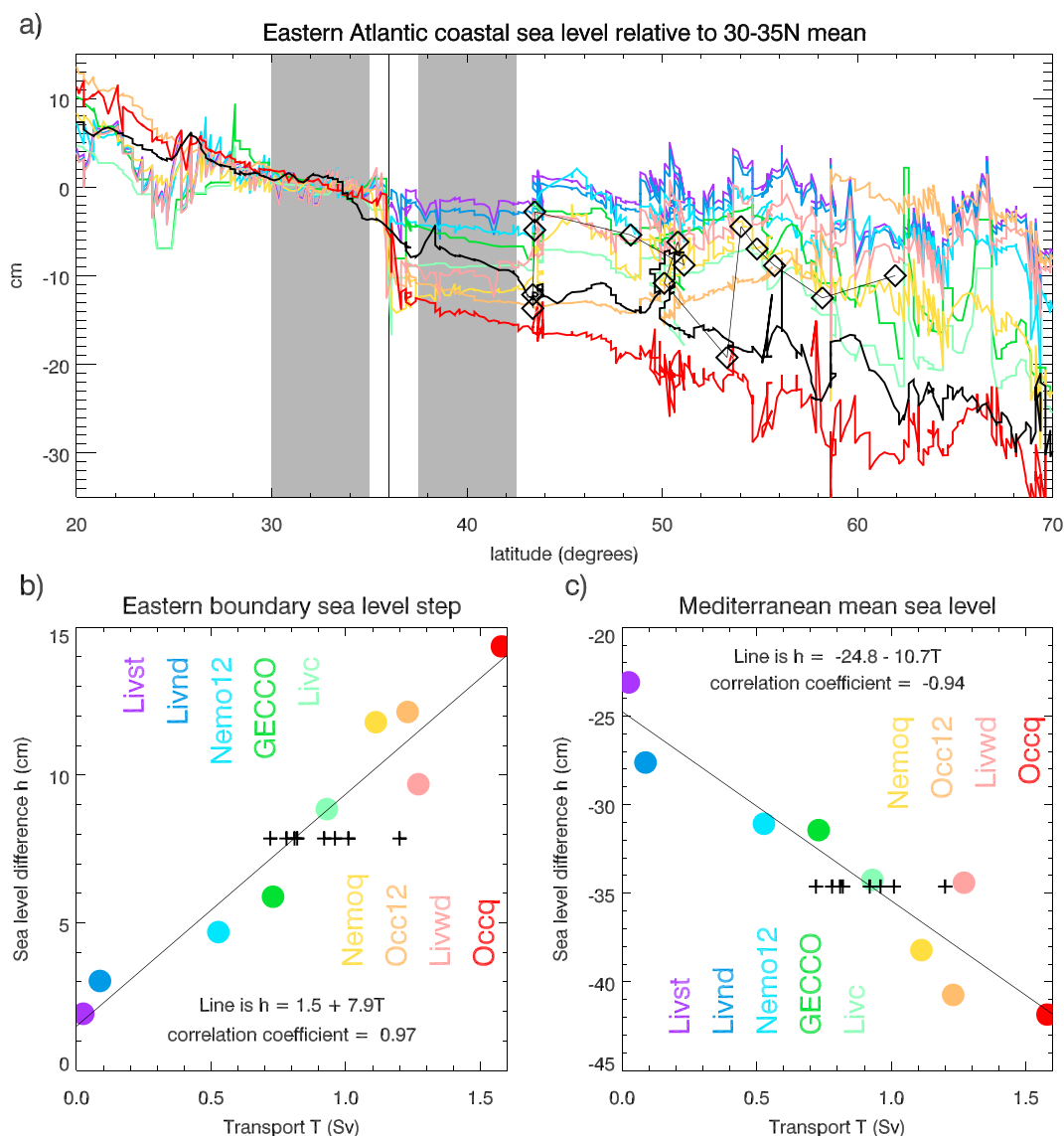


Figure 1. (a) Mean sea level measurements extracted from nine ocean models (colors), one observational product (thick black line), and tide gauges (thin black line with diamonds), showing profiles of coastal sea level along the eastern boundary of the Atlantic, excluding the Mediterranean and North Sea, aligned to have zero mean over the latitude range marked by the left-hand grey band. The Strait of Gibraltar is highlighted with a vertical line. (b) The sea level step across the Strait, determined by the differences of averages over the two grey bands in Figure 1a, plotted as a function of Mediterranean exchange transport in the models. (c) Difference between sea level averaged over the Mediterranean and over a region of the tropical North Atlantic (see text) as a function of model exchange transport. Black crosses in Figures 1b and 1c represent observational estimates, based on heights from this study (Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO) data), and transport estimates listed in Criado-Aldeanueva *et al.* [2012].

Comparing the Livst and Livwd model runs therefore allows us to isolate the effect of a change in just the Strait of Gibraltar. The resulting difference in sea level, normalized to represent the effect of a 1 Sv increase in the Mediterranean inflow (assuming a linear response), is shown in Figure 2a (the models are quasi-global, but changes are very small outside the area shown). The response is confined mainly to the Mediterranean and to the continental shelf and slope farther north, although it extends some distance into the deep ocean west of Portugal. The coastal response north of Gibraltar decreases from almost 8 cm Sv⁻¹ immediately north of the Strait, to about 3 cm Sv⁻¹ on the west coast of Great Britain, and less than 2 cm Sv⁻¹ along the Norwegian coast.

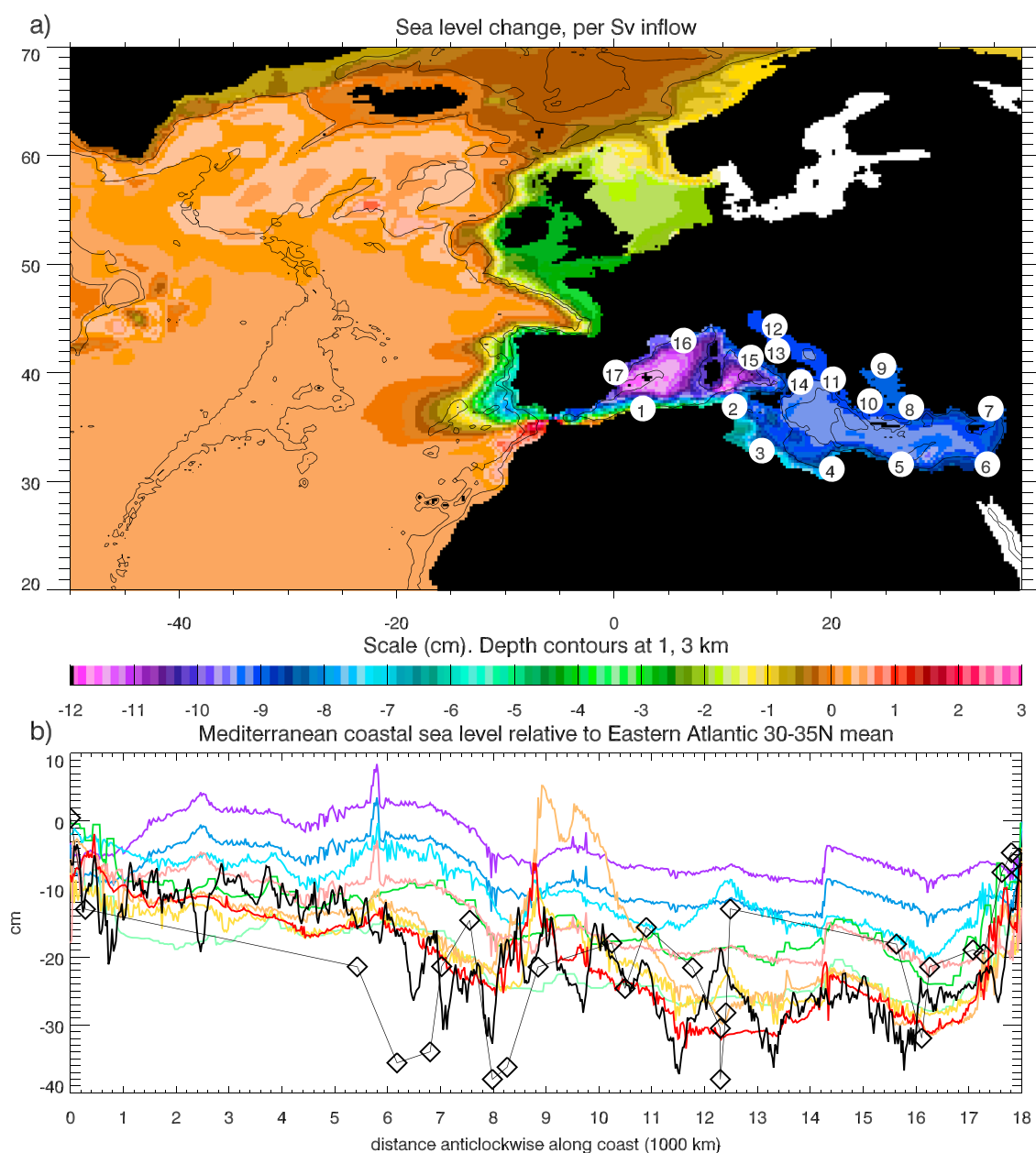


Figure 2. (a) The sea level change which would result from a 1 Sv Mediterranean exchange flow, from a twin experiment run for 13 months as described in the text. (b) As for Figure 1a, but for the Mediterranean coast, plotted as a function of anticlockwise distance from the Strait of Gibraltar, as marked by white circles in Figure 2a.

In addition to the coastal sea level drop north of the Strait, the twin experiment also highlights a fall in Mediterranean mean sea level when an exchange flow is present. In this particular case, the Mediterranean area mean sea level falls by 9.0 cm per sverdrup of exchange flow (the falls in Mediterranean and coastal European sea level are balanced by a near-uniform far-field global rise of 0.082 cm Sv^{-1}). The models with a significant exchange flow also consistently show Mediterranean coastal sea level to be lower than that in the nearby Atlantic (Figure 2b), suggesting a correlation across the nine models between the exchange flow and Mediterranean mean sea level measured relative to an appropriate North Atlantic reference region. Since information propagates northward along the continental slope and westward from the boundary into the interior (faster at lower latitudes), it makes dynamical sense for this reference region to be in the eastern basin, south of the Strait. Choosing for reference the triangular region north of 10°N and south of a line connecting $(10^\circ\text{N}, 45^\circ\text{W})$ and $(25^\circ\text{N}, 15^\circ\text{W})$, we find a correlation of -0.94 (Figure 1c). A linear regression

based on these points yields a Mediterranean response of -10.7 cm Sv^{-1} , similar to that seen in the twin experiment. Although this triangular region was chosen for the high correlation it produced, we found correlations stronger than -0.9 to be robust to the choice of reference region, considering the entire basin east of 30°W and a variety of latitude ranges between the equator and 25°N .

4. Comparison With Observed Sea Level

Given a good global map of sea level (by which we mean inverse barometer-corrected mean dynamic topography), the model relationships suggest two ways of using sea level to calculate the strength of Mediterranean exchange flow: using either the step in sea level between the African and European eastern Atlantic coasts or the difference between mean sea level in the Mediterranean and averaged over a region of the North Atlantic. Accordingly, we consider a 1996–2000 5 year average of the Duacs-2014 (V15.0) reprocessing of gridded satellite altimetry data from AVISO (<http://www.aviso.altimetry.fr/>), which incorporates geoid information from the Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite gravity mission. We use daily fields of the all-satellite, delayed processing, merged absolute dynamic topography product on the same quarter-degree grid as used for the model data. The black line without symbols in Figures 1a and 2b shows the coastal profile from this product, and the black crosses in Figures 1b and 1c show the corresponding coastal step and Mediterranean minus Atlantic sea level, together with the eight estimates of Mediterranean inflow summarized by *Criado-Aldeanueva et al.* [2012]. The black lines in Figures 1a and 2b show generally good agreement with the models, although the step at Gibraltar is spread out so that its step-like nature is not apparent (there may be a similar, spread-out step at about 25°N , just south of the Canaries; spreading of the steps at the coast may be expected from the need for extra smoothing of satellite-derived geoid data near ocean boundaries). There are also suggestions of different behavior north of about 44°N (the north coast of Spain). The observed Gibraltar step suggests an exchange flow of about 0.8 Sv . A formal fit based on the model data gives a transport of $0.80 \pm 0.15 \text{ Sv}$ (one standard deviation statistical error). Similarly, applying the model fit for exchange transport on sea level difference between the Mediterranean and the southeastern North Atlantic, the observed sea level predicts a transport of $0.91 \pm 0.20 \text{ Sv}$. Both observational measures are therefore consistent with a Mediterranean exchange flow within the $0.72\text{--}1.2 \text{ Sv}$ spread of in situ observational estimates.

Since altimetry and geoid measurements become less reliable near the coast, it is also worthwhile to look at the coastal dynamic topography based on tide gauge measurements. The ellipsoidal heights of tide gauge datums have been determined for 113 tide gauges around the North Atlantic and the Mediterranean. Mean sea surface heights for these gauges have been determined using data from the Permanent Service for Mean Sea Level [Holgate et al., 2013]. These were adjusted for the inverse barometer effect using air pressure information from the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalyses [Kistler et al., 2001] and converted to mean dynamic topographies by subtracting the TUM2013C geoid [Fecher et al., 2014] extended beyond spherical harmonic degree 720 with the EGM2008 coefficients [Pavlis et al., 2012]. Tide gauge measurements within 1993–2012 were employed, adjusted to the epoch 1996–2000 using nearby satellite altimetry data. More detailed information on the methodology of this calculation is given by [Woodworth et al., 2012], and a discussion of the Mediterranean tide gauge analysis and Mediterranean mean dynamic topography can be found in P. L. Woodworth et al. (The Mean Dynamic Topography of the Mediterranean Sea, submitted to *Journal of Geodesy*, 2014).

A vertical offset was applied to the tide gauge dynamic topography so that it can be treated as being measured relative to the $30\text{--}35^\circ\text{N}$ eastern boundary average, in the same way as the model data in Figures 1a and 2b. In the absence of any tide gauges in this reference region, this was achieved by aligning the average of the tide gauge data with the model and observational data at the same 113 points. The alignment was made to an average of the AVISO data and the two Nemo models, since these three data sets were found to agree best with the spatial variations in dynamic topography from the tide gauges, the two Nemo models being the only ones to agree better with the tide gauges than the AVISO data. Root-mean-square differences relative to the tide gauges were 8.5 cm for AVISO, 8.4 cm for Nemo12, and 7.8 cm for Nemoq, reducing to 7.3 cm for the mean of all three, and to below 5 cm if the 10 largest outliers are then successively removed. The full tide gauge set, following application of the vertical offset, is summarized in Figure S2. This allowed us to plot the tide gauge data (diamonds) in Figures 1a and 2b, with meaningful absolute values, for the subset of tide gauges which lie along the particular coasts depicted in the figures.

Although the tide gauge data are somewhat noisy, particularly on the Mediterranean coasts of North Africa, Israel, and Turkey, they are good enough to confirm the general picture of a Mediterranean level significantly lower than the European coastal sea level and suggest that the AVISO data north of Spain (about 43°N) may be somewhat lower than the true coastal sea level, which would then be more in line with most of the model predictions.

5. Discussion

While the relationship between exchange flow and the sea level drop between African and European coasts can be anticipated in a straightforward manner from geostrophic balance, the drop in Mediterranean mean sea level exposed by the twin experiment is a more subtle matter. It was first suggested more than 40 years ago, when *Levallois and Maillard* [1970] used the results of leveling, together with tide gauge records from 1950, to identify a 15 cm sea level fall between Cádiz (Atlantic coast) and Málaga (north Mediterranean coast). Such a fall is actually predicted by invoking hydraulically controlled flow through the Strait; assuming a state of maximal exchange producing a 1.1 Sv exchange flow, *Bormans and Garrett* [1989] predicted a sea level drop on entering the Mediterranean of 10 cm along a central streamline, and a drop of 21 cm along the northern boundary. *Garrett et al.* [1989] argue that tide gauge measurements suggest a maximal flow in the year 1981–1982, and *Timmermans and Pratt* [2005] support their argument for October 1984. However, later papers [*Garrett et al.*, 1990; *Ross et al.*, 2000] argue for an alternation between maximal and submaximal flow, the latter resulting in a much smaller midstream sea level fall. There are, therefore, theoretical arguments to support a difference between Mediterranean and Atlantic mean sea level of size similar to that which is observed. At seasonal and shorter timescales the fluctuations in Mediterranean mean sea level are clearly controlled by atmospheric pressure and wind stress changes, heat fluxes, and freshwater fluxes [*Fukumori et al.*, 2007].

The strong relationship between exchange transport and Mediterranean mean sea level, seen across nine very different models, combined with the reasonable transport predicted by comparing this relationship to sea level measurements, suggests that it may be a robust relationship. However, all of the models may be considered to be very low resolution in the Strait of Gibraltar. It might be possible to relate the exchange flow to the sea level drop using integral arguments which hold irrespective of resolution, but this cannot be guaranteed.

Another issue worth addressing is the relatively short length of model runs in the twin experiment. The runs are long enough for boundary waves, with speeds of 1 m s⁻¹ or faster, to propagate round the entire North Atlantic basin. On longer time scales, the Mediterranean exchange flow is known to influence regions far from the eastern boundary. For example, the Azores current, a zonal jet which flows east to the Mediterranean from about 37°W, is known to take about 5 years to develop in response to the Mediterranean exchange flow [*Volkov and Fu*, 2010; *Jia*, 2000; *Özgökmen et al.*, 2001]. The early stages of development of this current can be seen in Figure 2a, although the final current has a much stronger central jet of around 10 Sv transport, with only about 1 Sv entering the Mediterranean while the remainder recirculates in nearby counterjets driven by instability of the central current and in deeper flows as water is entrained by the Mediterranean overflow water [*Volkov and Fu*, 2010].

In our case, short model runs are necessary to avoid the confounding influence of sensitivity to eddy variability, which develops after approximately a year. An expensive ensemble run, beyond the scope of this study, would be necessary to separate the deterministic results of a changed Mediterranean flow from the stochastic changes due to perturbation of instabilities. However, we did investigate this issue by extending the Livwd model run to 5 years. By the fifth year, significant sea level differences were seen globally (including as far away as the tropical Pacific). On the Atlantic eastern boundary, we found that the sea level drop at the Strait penetrated farther north, with the Livwd line (pink) in Figure 1a shifting down between about 43°N and 58°N so that it almost covered the Livc line (pale green), despite an 11% drop in the Mediterranean exchange flow. However, the interior Atlantic changes degraded the fit between exchange flow and Mediterranean minus southeast Atlantic sea level, and we would caution against overinterpretation of this single, eddying model run.

6. Conclusions

Model comparisons have led to the identification of two mean sea level signals associated with the Mediterranean exchange flow through the Strait of Gibraltar: a step in sea level between the European and African coasts, and a lowering of the Mediterranean as a whole. Using measured sea level, these two relationships both lead to reasonable estimates for the exchange flow. Considering a central estimate of 0.85 Sv, the linear relationships shown in Figure 1 would mean the Mediterranean mean sea level is 9.1 cm lower and Portuguese coastal sea level is 6.7 cm lower than they would have been without such a flow (although there is a lower bound on the inward flow necessary to balance the net evaporation over the Mediterranean). Twin experiments suggest that the sea level step across the Strait of Gibraltar influences sea level along European coasts as far north as Norway, to an extent which decays with distance from Gibraltar. It is possible that, on longer time scales, this northern influence decays more gradually with distance from the Strait.

The large influence of the Mediterranean exchange flow highlights the importance of its representation in models if they are to be used to understand Atlantic eastern boundary mean sea level. Such understanding is a prerequisite for building trust in projections of long-term coastal sea level change. European coastal sea level variability on decadal time scales is dominated by a response to integrated longshore wind stress with typical amplitudes of 3–5 cm [Calafat *et al.*, 2012], but this is the longest time scale on which we can use time series observations from tide gauges and altimetry to test models. The spatial pattern of mean sea level gives access to a method for investigating the longer time scale processes responsible for maintaining the decimeter-scale alongshore slopes which exist in the mean.

Acknowledgments

This work has been supported by NERC through the National Oceanography Centre and the National Centre for Earth Observation, as well as through grants NE/H019812/1, NE/I023384/1, and NE/K012789/1, and by the European Space Agency. We thank AVISO for provision of the ocean dynamic topography product, and Thomas Gruber for help with geoid calculations. The ECCO ocean state estimates were provided by the ECCO Consortium for Estimating the Circulation and Climate of the Ocean funded by the National Oceanographic Partnership Program (NOPP). The OCCAM and NEMO models were run and provided by the NOC Southampton modeling group. We thank them and particularly Andrew Coward and Beverly de Cuevas for their help with these data sets. Satellite altimetry data used in this paper can be obtained from <http://www.aviso.altimetry.fr/>. Time series data from tide gauges can be found at <http://www.psmsl.org/>. Any other data used in this paper will be supplied by CWH on request by email.

The Editor thanks Don Chambers and an anonymous reviewer for their assistance in evaluating this paper.

References

- Armi, L., and D. M. Farmer (1985), The internal hydraulics of the Strait of Gibraltar and associated sills and narrows, *Oceanolog. Acta*, 8, 37–46.
- Bingham, R. J., and C. W. Hughes (2012), Local diagnostics to estimate density-induced sea level variations over topography and along coastlines, *J. Geophys. Res.*, 117, C01013, doi:10.1029/2011JC007276.
- Bormans, M., and C. Garrett (1989), The effects of nonrectangular cross section, friction, and barotropic fluctuations on the exchange through the Strait of Gibraltar, *J. Phys. Oceanogr.*, 19, 1543–1557.
- Blaker, A. T., J. J.-M. Hirschi, G. McCarthy, B. Sinha, S. Taws, R. Marsh, A. Coward, and B. de Cuevas (2014), Historical analogues of the recent extreme minima observed in the Atlantic meridional overturning circulation at 26°N, *Clim. Dyn.*, 44, 457–473, doi:10.1007/s00382-014-2274-6.
- Calafat, F. M., D. P. Chambers, and M. N. Tsimplis (2012), Mechanisms of decadal sea level variability in the eastern North Atlantic and the Mediterranean Sea, *J. Geophys. Res.*, 117, C09022, doi:10.1029/2012JC008285.
- Criado-Aldeanueva, F., F. J. Soto-Navarro, and J. García-Lafuente (2012), Seasonal and interannual variability of surface heat and freshwater fluxes in the Mediterranean Sea: Budgets and exchange through the Strait of Gibraltar, *Int. J. Climatol.*, 32, 286–302, doi:10.1002/joc.2268.
- Farmer, D. M., and L. Armi (1989), The flow of Atlantic water through the Strait of Gibraltar, *Prog. Oceanogr.*, 21, 1–105.
- Fecher, T., R. Pail, and T. Gruber (2014), Global gravity field modeling based on GOCE and complementary gravity data, *Int. J. Appl. Earth Obs. Geoinf.*, 35, 120–127, doi:10.1016/j.jag.2013.10.005.
- Fukumori, I., D. Menemenlis, and T. Lee (2007), A near-uniform basin-wide sea level fluctuation of the Mediterranean Sea, *J. Phys. Oceanogr.*, 37, 338–358.
- Garrett, C., J. Akerley, and K. Thompson (1989), Low-frequency fluctuations in the Strait of Gibraltar from MEDALPEX sea level data, *J. Phys. Oceanogr.*, 19, 1682–1695.
- Garrett, C., K. Thompson, and W. Blanchard (1990), Sea-level flips, *Nature*, 348, 292.
- Godfrey, J. S. (1988), A Sverdrup model of the depth-integrated flow for the World Ocean, allowing for island circulations, *Geophys. Astrophys. Fluid Dyn.*, 45, 89–112.
- Godfrey, J. S., and J. R. Dunn (2010), Depth-integrated steric height as a tool for detecting non-Sverdrup behaviour in the global ocean, *J. Mar. Res.*, 68, 387–412.
- Gray, A. R., and S. C. Riser (2014), A global analysis of Sverdrup balance using absolute geostrophic velocities from Argo, *J. Phys. Oceanogr.*, 44, 1213–1229.
- Holgate, S. J., A. Matthews, P. L. Woodworth, L. J. Rickards, M. E. Tamisiea, E. Bradshaw, P. R. Foden, K. M. Gordon, S. Jevrejeva, and J. Pugh (2013), New data systems and products at the Permanent Service for Mean Sea Level, *J. Coastal Res.*, 29, 493–504, doi:10.2112/JCOASTRES-D-12-00175.1.
- Huang, R. X. (1988), On boundary-value problems of the ideal-fluid thermocline, *J. Phys. Oceanogr.*, 18(4), 619–642.
- IHO IOC and BODC (2003), *Centenary Edition of the GEBCO Digital Atlas, Published on CD-ROM on Behalf of the Intergovernmental Oceanographic Commission and the International Hydrographic Organization as Part of the General Bathymetric Chart of the Oceans*, British Oceanographic Data Centre, Liverpool, U. K.
- Jia, Y. (2000), Formation of an Azores Current due to the Mediterranean overflow in a modeling study of the North Atlantic, *J. Phys. Oceanogr.*, 30, 2342–2358.
- Johnson, H. L., and D. P. Marshall (2002), A theory for the surface Atlantic response to thermohaline variability, *J. Phys. Oceanogr.*, 32(4), 1121–1132.
- Kinder, T. H. (1984), Net mass transport by internal waves near the Strait of Gibraltar, *Geophys. Res. Lett.*, 11(10), 987–990, doi:10.1029/GL011i010p00987.

- Kistler, R., et al. (2001), The NCEP-NCAR 50 year reanalysis: Monthly means CD-ROM and documentation, *Bull. Am. Meteorol. Soc.*, *82*, 247–267.
- Köhl, A., and D. Stammer (2008), Variability of the meridional overturning in the North Atlantic from the 50 years GECCO state estimation, *J. Phys. Oceanogr.*, *38*, 1913–1930, doi:10.1175/2008JPO3775.1.
- Levallois, J. J., and J. Maillard (1970), The new French 1st order levelling net. Practical and scientific consequences. Report on the Symposium on Coastal Geodesy, Munich 1970, 644 pp.
- Marsh, R., S. A. Josey, B. A. de Cuevas, L. J. Redbourn, and G. D. Quartly (2008), Mechanisms for recent warming of the North Atlantic: Insights gained with an eddy-permitting model, *J. Geophys. Res.*, *113*, C04031, doi:10.1029/2007JC004096.
- Marsh, R., B. A. de Cuevas, A. C. Coward, J. Jacquin, J. J. M. Hirschi, Y. Aksenov, A. J. G. Nurser, and S. A. Josey (2009), Recent changes in the North Atlantic circulation simulated with eddy-permitting and eddy-resolving ocean models, *Ocean Modell.*, *28*(4), 226–239, doi:10.1016/j.ocemod.2009.02.007.
- Morozov, E. G., K. Trulsen, and M. G. Velarde (2002), Internal tides in the Strait of Gibraltar, *J. Phys. Oceanogr.*, *32*, 3193–3206, doi:10.1175/1520-0485(2002)032<3193:ITISO>2.0.CO;2.
- Özgökmen, T. M., E. P. Chassignet, and C. G. H. Rooth (2001), On the connection between the Mediterranean outflow and the Azores Current, *J. Phys. Oceanogr.*, *31*, 461–480.
- Pavlis, N. K., S. A. Holmes, S. C. Kenyon, and J. K. Factor (2012), The development and evaluation of the Earth Gravitational Model 2008 (EGM2008), *J. Geophys. Res.*, *117*, B04406, doi:10.1029/2011JB008916.
- Ross, T. K., C. Garrett, and P.-Y. L. Traon (2000), Western Mediterranean sea-level rise: Changing exchange flow through the Strait of Gibraltar, *Geophys. Res. Lett.*, *27*, 2949–2952, doi:10.1029/2000GL011653.
- Smith, D. M., and J. M. Murphy (2007), An objective ocean temperature and salinity analysis using covariances from a global climate model, *J. Geophys. Res.*, *112*, C02022, doi:10.1029/2005JC003172.
- Thomas, M. D., A. M. de Boer, H. L. Johnson, and D. P. Stevens (2014), Spatial and temporal scales of Sverdrup balance, *J. Phys. Oceanogr.*, *44*, 2644–2660, doi:10.1175/JPO-D-13-0192.1.
- Timmermans, M.-L. E., and L. J. Pratt (2005), Two-layer rotating exchange flow between two deep basins: Theory and application to the Strait of Gibraltar, *J. Phys. Oceanogr.*, *35*, 1568–1592.
- Tsimplis, M. N., and H. L. Bryden (2000), Estimation of the transports through the Strait of Gibraltar, *Deep Sea Res.*, *1*, 47, 2219–2242.
- Volkov, D. L., and L.-L. Fu (2010), On the reasons for the formation and variability of the Azores Current, *J. Phys. Oceanogr.*, *40*, 2197–2220.
- Williams, R. G., V. Roussenov, D. Smith, and M. S. Lozier (2014), Decadal evolution of ocean thermal anomalies in the North Atlantic: The effects of Ekman, overturning, and horizontal transport, *J. Clim.*, *47*, 698–719, doi:10.1175/JCLI-D-12-00234.1.
- Woodworth, P. L., C. W. Hughes, R. J. Bingham, and T. Gruber (2012), Towards worldwide height system unification using ocean information, *J. Geodetic Sci.*, *2*(4), 302–318, doi:10.2478/v10156-012-0004-8.
- Wunsch, C. (2011), The decadal mean ocean circulation and Sverdrup balance, *J. Mar. Res.*, *69*(2–3), 417–434.

Supporting Information for “The effect of Mediterranean exchange flow on European time-mean sea level”

Chris W. Hughes,^{1,2} Rory J. Bingham,³ Vassil Roussenov,¹ Joanne Williams²
and Philip L. Woodworth²

Contents of this file

1. Figures S1 to S2

Introduction This supplementary information consists of two Figures showing data giving broader context to the figures shown in the paper. The first extends the model and altimeter datasets to show a wider latitude range, and the second shows dynamic topog-

Corresponding author: Chris W. Hughes, School of Environmental Sciences, University of Liverpool, Jane Herdman Building, Liverpool L69 3GP, U.K. (cwh@liv.ac.uk)

¹School of Environmental Sciences,
University of Liverpool, Liverpool, U.K.

²National Oceanography Centre,
Liverpool, U.K.

³School of Geographical Sciences,
University of Bristol, Bristol, U.K.

raphy at the full 113 tide gauges used in the study, of which only a subset are shown in the main figure.

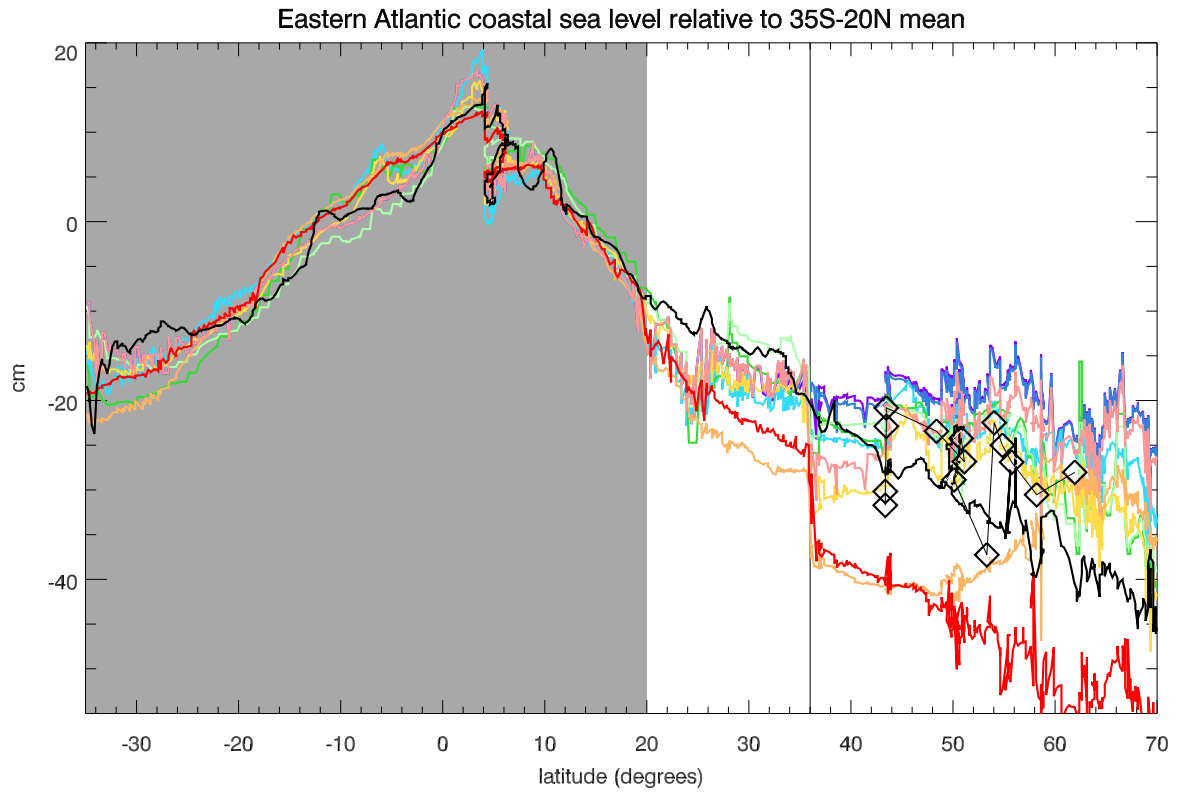


Figure S1. Atlantic coastal mean sea level curves as in Figure 1a, but aligned so that the averages over the grey band are equal. Vertical black line shows the latitude of the Strait of Gibraltar.

Figure S2. Mean (1996-2000) dynamic topography at North Atlantic and Mediterranean tide gauges (black), and from the nearest grid point in a reference field made by averaging the AVISO data and the two NEMO ocean models (blue), plotted relative to the 30–35°N eastern Atlantic coastal average of that field. A uniform vertical shift has been applied to the tide gauge data to minimise the differences from the reference field. Tide gauge names are as given by the Permanent Service for Mean Sea Level

